Transient Response Analysis of the Monopole Antenna Illuminated by an External EMP Source

Qifeng Liu, Xiaonan Zhao
Science and Technology on EMC Laboratory
China ship development and design center
Wuhan, China
emclqf@126.com

Jingwei Liu
Huazhong University of Science & Technology,
1037 Luoyu Road,Wuhan, China
179462829@qq.com

***Abstract*—Investigation on time-domain responses of the monopole in the presence of an in intentional electromagnetic pulses (EMP) is carried out in this conference paper. An efficient hybrid numerical method based on FDTD method combined with the thin-wire model using subcellular extension is implanted for studying an EMP coupling with some typical monopole antennas widely used in the communication systems. Our developed program code is used to capture the responses of the monopole antenna. The transient response characteristics of the antenna illuminated by different incident EMPs are shown and compared in detail. These results are useful for further evaluating electromagnetic environment and electromagnetic protection of some complex communication.**

Keywords-Electromagnetic pulses (EMP); monopole antenn; transient response; FDTD.

I. INTRODUCTION

In the past one century, the monopole antenna has been seen widely spread in the short-wave and ultrashort wave communication system for different platforms, especially for the close quarters communication and telecommunication between the ships and fleets.

On the other hand, it should be understood that electromagnetic environment around us is now becoming more and more complex, because the number of electromagnetic interference (EMI) sources existed is being increased rapidly. Actually, most of communication systems are very sensitive and susceptible to EMI and in particular to an intentional electromagnetic interference (IEMI).

IEMI refers to “intentional malicious generation of electromagnetic energy introducing noise or signals into electrical and electronic systems, thus disrupting, confusing, or damaging the systems for terrorist or criminal purposes” [1]. Such an intentional interfering electromagnetic energy can be generated by a non-explosive high-power microwave source [2], and even a very powerful ultra-wide band pulse antenna.

The IEMI usually works in the following way:(a) an intentional high-power or ultra-wide band electromagnetic pulse is suddenly generated and it is incident on to antennas, metallic enclosure with slots, and transmission lines of the communication system through direct radiation or indirect capacitive or inductive coupling; and(b) as a result, it then causes high voltage, large current and rapid temperature rise or thermal stress in the inner circuit which may result in electrical or thermal breakdown and even destruction of the system[3].

With respect to IEMI coupling paths with most communication systems, we should at first take radiation coupling between the IEMI and the antenna into account.

Further, we know that the analysis of antenna characteristics in the time domain has been carried out extensively in the past two decades for the sake of the time domain method can effectively capture wideband information and handle nonlinear problems. Among various numerical methods, time-domain finite difference (FDTD) is frequently implanted to solve transient radiation and scattering problem. Conventional thin-wire FDTD techniques can be classified into four approaches: the auxiliary differential [4], the contour-path integration [5], the weighted residual interpretation [6], and the modified of assigned material parameters [7]. These techniques have been improved by arbitrary orientation [8], cylindrical field behavior around the wires [9] and the concept of effective radius.

Recently, a resistive thin-wire FDTD model with both the insulating and surrounding media being lossless and loss has been proposed [10], and the antenna excited by the coaxial lines is simulated by an equivalent model without any additional transmission line (TL) cell modeling.

In this paper, we first improve the thin-wire model using subcellular extension [10] in the orthogonal coordinate system, and then a numerical procedure based on thin-wire scheme of FDTD to characterize transient pulse responses of some communication monopole antennas. This paper is organized as follows.

978-1-4673-6079-1/13/$31.00 ©2013 IEEE

In section II, the thin-wire model using subcellular extension in the orthogonal coordinate system based on the method of time-domain finite difference is presented. In section III, some numerical investigations are carried out to explore the transient effects of an incident EMP on some communication antennas, with feed–point transient voltage obtained and compared with the measurements. Some conclusions are made in Section IV.

II. FROMULATION

A. The Time-domain finite difference method

Since the time-domain finite difference (FDTD) is proposed by 1966, it developed fast, and has been implanted in many fields. The FDTD technique is a computationally efficient means of directly solving Maxwell's time domain-dependent curl equations of their equivalent integral equations using the finite-difference technique. The FDTD discrete the spatial domain by the Yee cell and the curl equations approximately by the second-order finite difference.

The EMC/EMI problems can be considered to solve the Maxwell equations on the special boundary condition, for the opening region problem, the boundary condition is the radiation boundary. Time-domain Maxwell is as follows:

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \tag{2-1a}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} - \mathbf{J}_m \tag{2-1b}$$

$$\nabla \cdot \mathbf{B} = \rho_m \tag{2-1c}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{2-1d}$$

where $\mathbf{H}$ is magnetic field distribution, $\mathbf{B}$ is magnetic flux density distribution, $\mathbf{E}$ is electric field distribution, and $\mathbf{D}$ is electric flux density distribution. In the orthogonal coordinate system, the two curl equations can be written as:

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = \varepsilon \frac{\partial E_x}{\partial t} + \sigma E_x \tag{2-2a}$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = \varepsilon \frac{\partial E_y}{\partial t} + \sigma E_y \tag{2-2b}$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = \varepsilon \frac{\partial E_z}{\partial t} + \sigma E_z \tag{2-2c}$$

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\mu \frac{\partial H_x}{\partial t} - \sigma_m H_x \tag{2-3a}$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\mu \frac{\partial H_y}{\partial t} - \sigma_m H_y \tag{2-3b}$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\mu \frac{\partial H_z}{\partial t} - \sigma_m H_z \tag{2-3c}$$

Based on the Yee cell, we can use a centered finite-difference approximation with the second-order accuracy with respect to x-, y-, and z-coordinate variable or time variable t, and finally obtain the updated equations for electric field component E_x , E_y and magnetic field component H_x , H_y and H_z . For the opening region problem, the absorbing boundary condition (ABC) is used to truncate the solving domain.

B. The equivalent resistive thin-wire FDTD model

Recently, a resistive thin-wire FDTD model has been proposed, and the antenna excited by the coaxial lines is simulated by an equivalent model without any additional transmission line (TL) cell modeling [10]. Now the thin-wire FDTD model is improved to analyze the transient response of the linear monopole antenna. By the quasi-static approximation, the aperture in Fig.1 (a) can be represented by the magnetic frill current, and according the transmission line theory, the total voltage at the aperture equals the superposition of the incident and the reflected voltage, respectively, as:

$$V_{ab}(t) = V_{inc}(t) + V_{ref}(t) \tag{2-4}$$

If the characteristic impedance is Z_0 , the reflected voltage at the aperture can be written as:

$$V_{ref}(t) = V_{inc}(t) - Z_0 I \tag{2-5}$$

Considering the propagation mode is the TEM mode, so the equivalent magnetic frill current can be written as:

$$M(x, y, t) = [-2V_{inc}(t) + Z_0 I(t)]/[a \ln(b/a)] \tag{2-6}$$

According to the Ampere's law, the total current at the feed point can be calculated as:

$$\begin{aligned} I^n = {} & \Delta y[H_y^n(i_f + \tfrac{1}{2}, j_f, k_f) - H_y^n(i_f - \tfrac{1}{2}, j_f, k_f)] \\ & - \Delta x[H_x^n(i_f, j_f + \tfrac{1}{2}, k_f) - H_y^n(i_f, j_f - \tfrac{1}{2}, k_f)] \end{aligned} \tag{2-7}$$

Further, the update equation for the magnetic field at feed point can be expressed as:

$$\begin{aligned} H_y^{n+\frac{1}{2}}(i_f + \tfrac{1}{2}, j_f, k_f) = {} & H_y^{n-+\frac{1}{2}}(i_f + \tfrac{1}{2}, j_f, k_f) \\ & - \frac{\Delta t}{\mu_0 \Delta z} E_x^n(i_f + \tfrac{1}{2}, j_f, k_f) \\ & + \frac{2\Delta t}{\mu_0 \Delta x \ln \frac{\Delta x}{a}} E_z^n(i_f + 1, j_f, k_f) \\ & - \frac{2\Delta t}{\mu_0 \Delta z \ln \frac{\Delta x}{a}} (-2V_{inc}^n + Z_0 I^n) / \Delta x \end{aligned} \tag{2-8a}$$

$$\begin{aligned} H_x^{n+\frac{1}{2}}(i_f, j_f + \tfrac{1}{2}, k_f) = {} & H_x^{n-\frac{1}{2}}(i_f, j_f + \tfrac{1}{2}, k_f) \\ & + \frac{\Delta t}{\mu_0 \Delta z} E_y^n(i_f, j_f + \tfrac{1}{2}, k_f) \\ & - \frac{2\Delta t}{\mu_0 \Delta y \ln \frac{\Delta y}{a}} E_z^n(i_f, j_f + 1, k_f) \end{aligned}$$

$$+\frac{2\Delta t}{\mu_0 \Delta z \ln\frac{\Delta y}{a}}(-2V_{inc}^{n}+Z_0 I^{n})/\Delta y \quad (2\text{-}8b)$$

The update equation for the magnetic field at the other Yee cell in Fig.1 (b) can also be obtained according the the Ampere's law as follows:

$$H_y^{n+\frac{1}{2}}(i_a+\tfrac{1}{2},j_a,k_a+\tfrac{1}{2})=H_y^{n-\frac{1}{2}}(i_a+\tfrac{1}{2},j_a,k_a+\tfrac{1}{2})$$

$$-\frac{\Delta t}{\mu_0\Delta z}[E_x^n(i_a+\tfrac{1}{2},j_f,k_f+1)-E_x^n(i_a+\tfrac{1}{2},j_f,k_f)]$$

$$+\frac{2\Delta t}{\mu_0\Delta x\ln\frac{\Delta x}{a}}E_z^n(i_a+1,j_a,k_a+\tfrac{1}{2}) \quad (2\text{-}9a)$$

$$H_x^{n+\frac{1}{2}}(i_a,j_a+\tfrac{1}{2},k_a+\tfrac{1}{2})=H_x^{n-\frac{1}{2}}(i_a,j_a+\tfrac{1}{2},k_a+\tfrac{1}{2})$$

$$-\frac{\Delta t}{\mu_0\Delta z}[E_y^n(i_a,j_a+\tfrac{1}{2},k_a+1)-E_y^n(i_a,j_a+\tfrac{1}{2},k_a)]$$

$$+\frac{2\Delta t}{\mu_0\Delta y\ln\frac{\Delta x}{a}}E_z^n(i_a,j_a+1,k_a+\tfrac{1}{2}) \quad (2\text{-}9b)$$

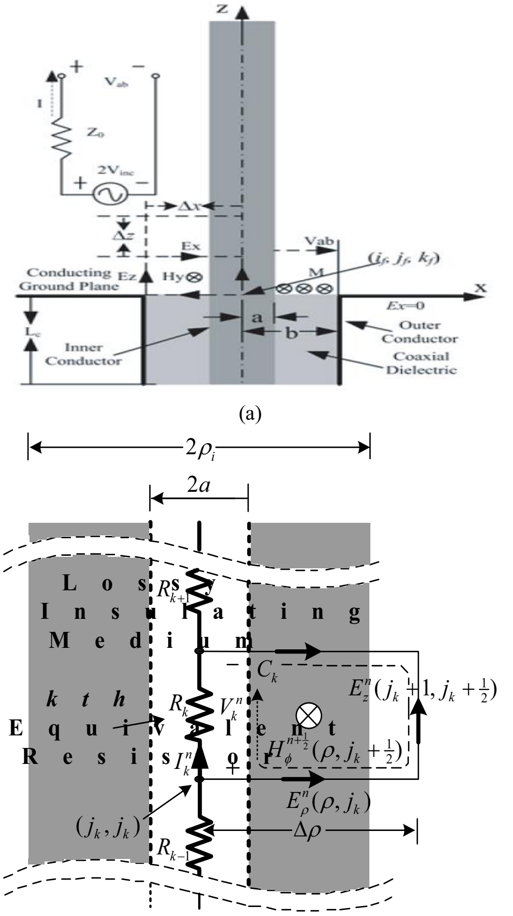

Fig.1 the adjacent Yee cell and the structure of the monopole antenna(a)The equivalent resistive thin-wire FDTD model(b)the FDTD updated cell.

C. Intentional EMI Exciting Pulse

According to the experimental date present of the high-power wideband electromagnetic pulse source in [11], an analytical equation that describes the waveform is found as follows.

$$E(t)=\sum_{i=1}^{6}E_i\, e^{-\left(\frac{t-t_i}{w_i}\right)^2}, \quad (10)$$

Where the fitting coefficient E_i , t_i and w_i are understood, but suppressed here.

On the other hand, we also suppose the incident EMP can be a slow-, medium-, and fast-EMP, respectively, which described by the two exponential functions realized by the parameters α and β [12].

$$E_\alpha(t)=E_0 k(\alpha,\beta)(e^{-\beta t}-e^{-\alpha t}) \quad (11a)$$

$$k(\alpha,\beta)=(e^{-\beta\frac{\ln(\alpha)-\ln(\beta)}{\alpha-\beta}}-e^{-\alpha\frac{\ln(\alpha)-\ln(\beta)}{\alpha-\beta}}) \quad (11b)$$

III. NUMERICAL RESULTS AND DISCUSSIONS

Based on the above mathematical, computer code are developed for the performing the transient electromagnetic responses of the wideband monopole antennas illuminated by an external electromagnetic pulse with different waveforms and parameters above presented.

Next we consider a monopole antenna mounted on a finite size ground, shown in Fig. 2. The cylindrical antenna is connected to the front-end by the coaxial line. The height of the vertical cylinder conductor is h , the inner an outer radii of the coaxial line is a and b , respectively. The ratio b/a is set to be 2.3, for this problem.

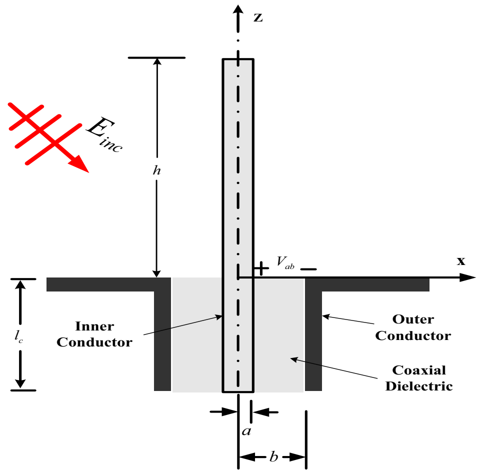

Fig. 2. A monopole antenna with coaxial lien illuminated by an external EMP.

The FDTD cell size is selected as $\Delta x=\Delta y=1.4605$ mm and $\Delta y=0.635$ mm. The time increment is chosen to satisfy the Courant-Friedrichs-

Levy (CFL) condition as $\Delta t = \Delta y / 2c_0$, where c_0 denotes the light velocity. The unaxial perfect matched layer (UPML) is implanted to truncate the computation domain [13].

When the monopole antenna is illuminated by external EMP source, the induced current and voltage will produce at the feed point of the antenna, and further the induced energy will propagate along the transmission system into the front-end part, and may bring the interfere, even the physical damage to the electric system, so it is important to capture the transient response of the monopole antenna which widely used in shortwave communications systems. Figure3 show the induced voltage at the feed point when the monopole antenna illuminated by the EMP source [10]. From the figure, it is found that the magnitude of the induced voltage as high as 19.8 kV.

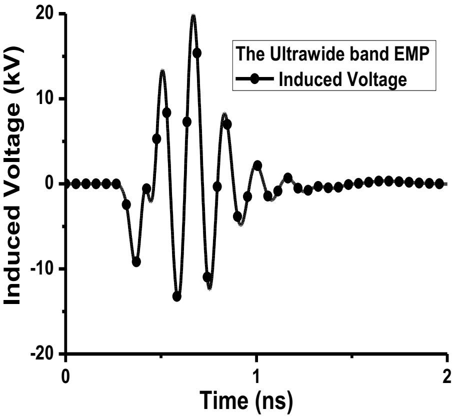

Fig. 3. The transient response of the induced voltage on the feed point.

Finally, in addition to the high-power wideband electromagnetic pulse present in equation (10), we further impose an low-, medium-, and fast-EMP of $E_0 = 50\ kV/m$ illuminated onto the investigated monopole antenna, respectively.

Fig.4 shows the transient voltage response on the feed point of the monopole antenna in Fig.2, which is also illuminated by a high-power fast-, medium-and slow-EMP, respectively. It is shown that among three types of intentional high-power EMP incidence, the fast-EMP excites the strongest coupled voltage in time and spectral domain on the feed point of the monopole antenna.

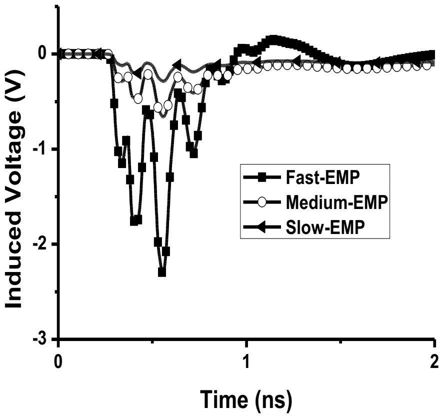

Fig. 4. The transient response of the induced voltage on the feed point. (a)slow-EMP; (b) medium-EMP; and (c) fast-EMP, respectively.

IV. CONCLUSION

In this paper, a resistive thin-wire FDTD model is improve and applied to efficiently simulate the linear monopole antenna. The numerical procedure is developed for capturing the transient response of monopole antennas, and compared with different incident source parameters. Various numerical results were presented to demonstrate the transient responses characteristic of the monopole antenna. This study can severe as the first step and input terms for the planning of electromagnetic pulse protection of these special antennas against the high-power EMP sources.

REFERENCES

[1] D. V. Giri, and F. M. Tesche, "Classication of intentional elec tromagnetic environments(IEME)," IEEE Trans. Electromagn. Compat., Vol.46, No.3, pp.322-328, Aug. 2004.

[2] Q. F. Liu, W. Y. Yin, M. F. Xue, J. F. Mao, and Q. H. Liu "Shielding characterization of metallic enclosures with multiple slots and a thin wire antenna loaded: multiple oblique EMP incidence with arbitrary polarization," IEEE Trans. Electromagn. Compat., vol. 51, no. 2, pp. 284-292, May 2009.

[3] J. F. Xu,W. Y. Yin, J. F. Mao, and L. W. Li, "Thermal transient response of GaAsFETs under intentional electromagnetic interference(IEMI)," IEEE Trans. Electromagn. Compat., Vol.50, No.2, pp. 340-346, May 2008.

[4] R. M. Makinen, J. S. Juntunen, and M. A. Kivikoski, "An improved thin-wire model for FDTD," IEEE Trans. Microw. Theory Tech., 2002, 50(5): 1245–1255.

[5] C. J. Railton, B. O. Koh, and I. J. Craddock, "The treatment of thin wires in the FDTD method using a weighted residual approach," IEEE Trans.Antennas Propag., 2004, 52(11): 2941–2949.

[6] T. Noda and S. Yokoyama, "Thin wire representation in finite difference time domain surge simulation," IEEE Trans. Pow. Del., 2002, 17(3): 840–847.

[7] C. J. Railton, D. F. Paul, I. J. Craddock, and G. S. Hilton, "The treatment of geometrically small structures in FDTD by the modification of assigned material parameters," IEEE Trans. Antennas Propag., 2005, 53(12): 4129–4136.

[8] F. Edelvik, "A new technique for accurate and stable modeling of arbitrary oriented thin wires in the FDTD method," IEEE Trans. Electromagn. Compat., 2003, 45(2): 88–97.

[9] Y. Taniguchi, Y. Baba, N. Nagaoka, and A. Ametani, “Representation of an arbitrary-radius wire for FDTD calculations in the 2D cylindrical coordinate system,” IEEE Trans. Electromagn. Compat., 2008, 50(4): 427–31.

[10] S. Y. Hyun, and S. Y. Kim, “Thin-wire model using subcellular extensions in the finite-difference time-domain analysis of thin and lossy insulated cylindrical structures in lossy media,” IEEE Trans. Electromagn. Compat., 2009, 51(4): 1009–1016.

[11] W.A. Radasky, C. E. Baum, and M. W. Wik, “ Introduction to the special issue on high-power electromagnetics (HPEM) and intentional electromagnetic interference (IEMI),” IEEE Trans. Electromagn. Compat., vol.46, no.3, 314-321, Aug. 2004.

[12] M. Camp, and H. Garbe, “Parameter estimation of double exponential pluses (EMP, UWB) with least squares and nelder mead algorithm,” IEEE Trans. Electromagn. Compat., 2004, 46(4): 368-379.

[13] A. Taflove and S. C. Hagness, Computational Electrodynamics: The Finite-Difference Time-Domain Method, second edition. Norwood, MA: Artech House, 2000.